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INTERFEROMETRIC MEASUREMENT OF LOW-FREQUENCY PHASE NOISE OF AN EXTERNAL CAVITY SEMICONDUCTOR LASER

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ABSTRACT

The external cavity laser is a good candidate for use in the development of interferometric fiber sensors with small path length differences. This report summarizes an interferometric measurement of phase noise characteristics of a Hewlett-Packard external cavity laser operating in the 1550 nm wavelength band. The measurement was made using an unbalanced Mach-Zehnder fiber interferometer. This result is more than an order of magnitude lower than typically observed with semiconductor diode lasers, but nearly two orders of magnitude greater than that observed for a diode laser-pumped solid-state Nd:YAG laser.

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INTRODUCTION

Interferometric fiber optic sensor systems typically use highly coherent, narrow linewidth, single frequency light sources. Although a low phase noise Nd:YAG laser has been identified[1], the Nd:YAG laser operates at 1319 nanometers (nm) and has a fixed wavelength output. For some systems it may be desirable to have a laser that is tunable in wavelength. Also, operating in the 1550 nm telecommunications band is advantageous due to the availability of direct optical amplification with erbium doped fiber amplifiers. One such source is an external cavity laser, which can have a laser linewidth of approximately 100 kHz. This laser exhibits a long coherence length and thus low phase noise and is suitable for demonstrating the sensitivity of fiber interferometers to pressure.

Because of path length mismatches between the two interferometer paths, instability of the laser results in interferometric phase noise. The magnitude of the phase noise, $\Delta\phi_N$, is dependent upon the path length mismatch ΔL and can be expressed as

$$\Delta\phi_N = \frac{2\pi n \Delta L \Delta \upsilon}{c} \; , \tag{1}$$

where $\Delta\upsilon$ is the rms laser frequency instability, n is the fiber index of refraction, and c is the speed of light. The laser frequency instability is caused by two mechanisms. A spontaneously emitted photon will change the optical phase within the device by a random amount that leads to a frequency shift. Second, the emission of a photon will cause changes in the gain of the laser, or equivalently, the carrier population. Changes in carrier population lead to a frequency fluctuation due to the change in refractive index of the laser[2,3].

This report summarizes an interferometric measurement of phase noise characteristics of a Hewlett-Packard external cavity laser, model number 8168A, operating in the 1550 nm wavelength band. Figure 1 shows a schematic of the internal configuration of the laser. It consists of a diode laser with one facet that is a high reflector and the other facet coated with an anti-reflection (AR) coating for low reflectivity. The output from the AR coated facet is diffracted back on itself by a diffraction grating, which narrows the cavity optical pass band. An etalon is used to further narrow the cavity optical pass band. Tuning is achieved by controlling the angle of incidence of both the grating and the etalon. The diode laser, which typically has a cavity extending from the front facet to the rear facet of the diode, now has an "external cavity" extending beyond the rear facet of the diode to the diffraction grating. Such techniques can narrow the typical diode spectrum of $6X10^{20}$ Hz (5 nm) to a single line that is less than 100 kHz ($8X10^{-16}$ nm). The result is a highly coherent, narrow linewidth tunable laser. The HP external cavity specified 100 kHz laser linewidth corresponds to a coherence length of 3000 meters. The wavelength tuning range is from 1500 nm to 1565 nm.

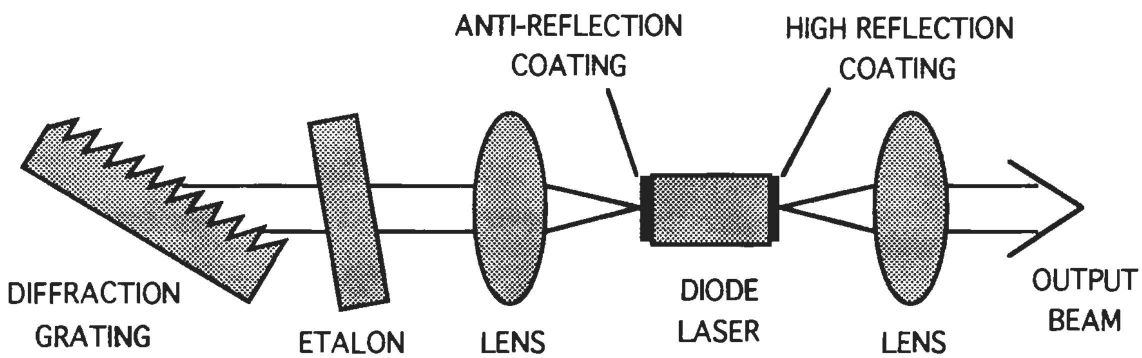

Figure 1. Schematic of External Cavity Laser

MEASUREMENT DESCRIPTION

The experimental arrangement to measure the low-frequency phase noise of the laser is shown in figure 2. To provide an interferometric system with a very high resolution for

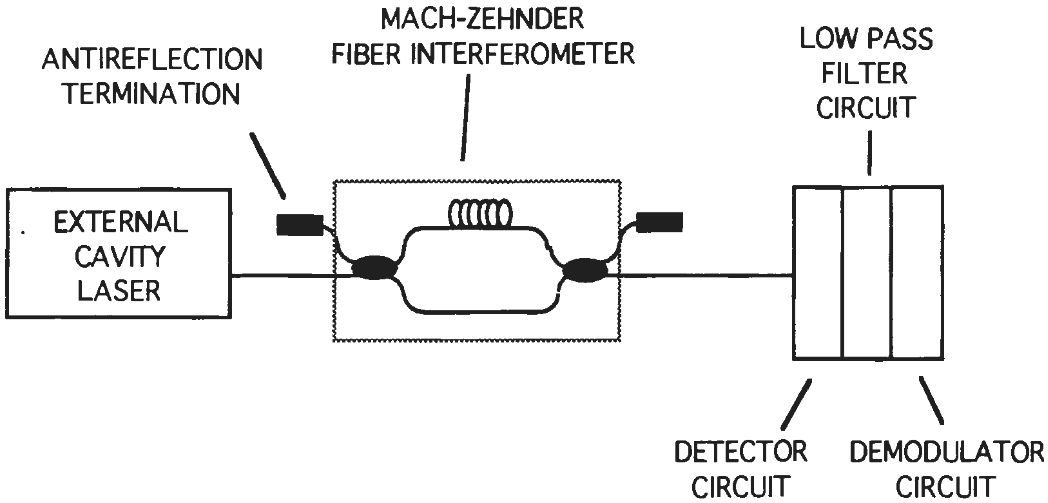

Figure 2. Schematic of Experimental Arrangement to Measure Laser Phase Noise

optical frequencies, an all-fiber Mach-Zehnder interferometer configuration with an 80-m fiber imbalance between its two paths was used. The interferometer was encapsulated in a housing specially designed to shield it from environmental noise sources, such as acoustic noise. A small piezoelectric fiber stretcher was incorporated into one arm of the interferometer to generate an optical phase carrier. This is necessary to use the phase generated carrier demodulation technique to measure the phase noise[4].

TEST RESULTS

Figure 3 shows the results of these measurements over a range of 10 Hz to 2.5 kHz. The measured phase noise at a frequency of 1 kHz was 2 $mrad/\sqrt{Hz}$, corresponding to a laser frequency jitter of 800 $Hz/\sqrt{Hz}$. This result is more than an order of magnitude lower than that typically observed with semiconductor diode lasers, but nearly two orders of magnitude greater than that observed for a diode laser-pumped solid-state Nd:YAG laser[1].

Figure 4 is a plot of the time series for the laser phase noise. Of particular importance is the low frequency modulation at approximately 34 Hz and the 15 Volt peak-to-peak voltage. This high level voltage is nearly at the 28 Volt limit of the electronics.

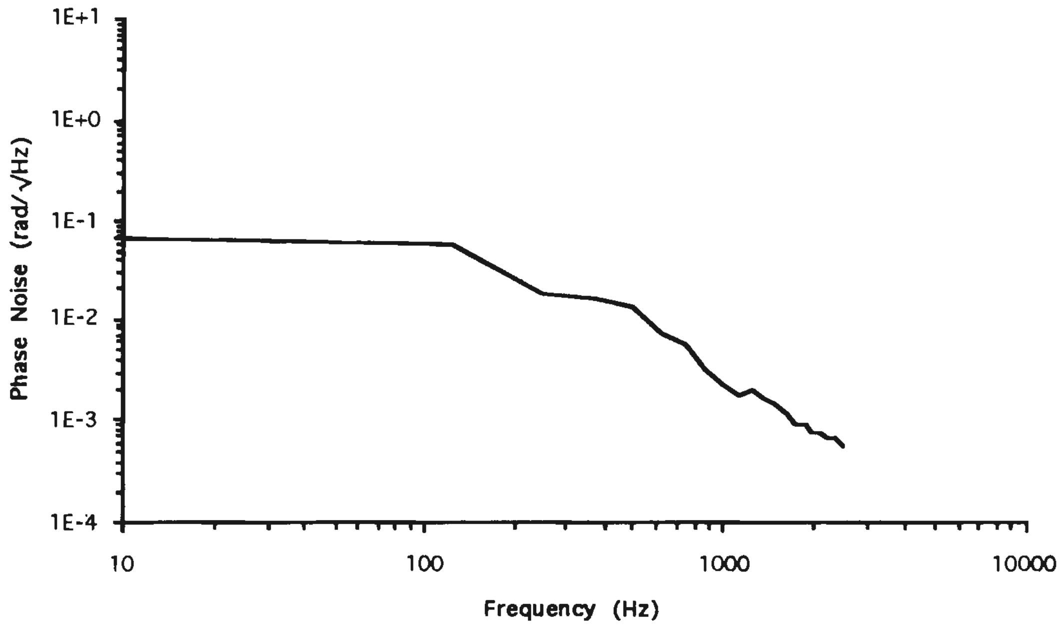

Figure 3. Laser Phase Noise With an Optical Path Difference of 80 m for an HP External Cavity Laser

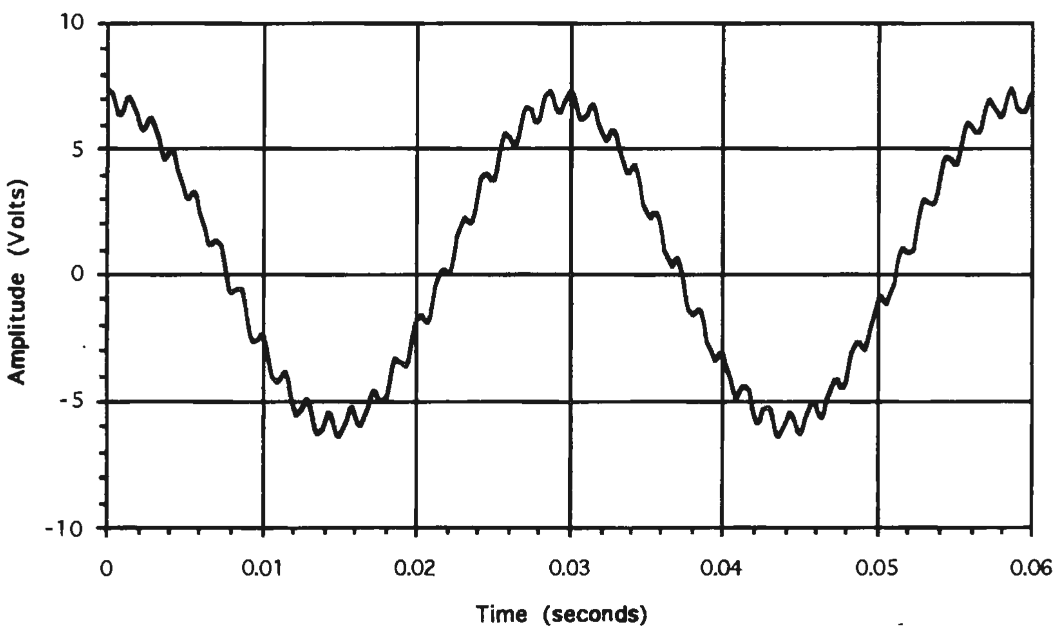

Figure 4. Time Series of Demodulator Output

Laser resonant cavities are particularly sensitive to thermal, acoustic, and mechanical vibrational perturbations due to their high Q. This is especially important where the laser resonant cavity is long relative to the wavelength of the perturbation, such as the case with an external cavity configuration. Typical diode laser cavities are approximately 300 μm in length versus centimeters for external cavity lasers. These concerns warrant a description of the sensitivity of the laser to mechanical and acoustic vibration. The laser cavity is packaged in an enclosure together with all supporting electronics and a small fan to circulate air in the enclosure. A measurement of the laser phase noise with the internal fan "off", can give some insight into the vibrational sensitivity of the laser. Figure 5 shows a measurement of phase noise for the case with the fan turned "off", compared to that of the fan turned "on". Below 700 Hz there is an order of magnitude reduction in laser phase noise. As shown in figure 5, the dependence of phase noise of the external cavity laser with the fan "off" is falling off at a slope of 1/f above 250 Hz. A 1/f dependence was also measured for an Nd:YAG laser[1]. The time series of the demodulator output for the case of the fan "off" is very similar to that of figure 4, with the exception that the amplitude was reduced to 8.5 Volts peak-to-peak.

Typically a Lissajous pattern, generated by sine and cosine signal components from the demodulator, is monitored to qualitatively assess the performance of the system. Ideally, the Lissajous pattern consists of a point that lies on the perimeter of a perfect circle. Any optical phase change is perceived as a finite length arc (representing the amplitude of the signal), which oscillates between the endpoints of the arc at the signal frequency. Any deviation from a perfect circle indicates changes in the interferometric signal optical power level (typically due to polarization changes) at a rate that exceeds the update rate of the automatic gain control of the demodulator. Figure 6 shows sketches of the Lissajous figures for this experiment.

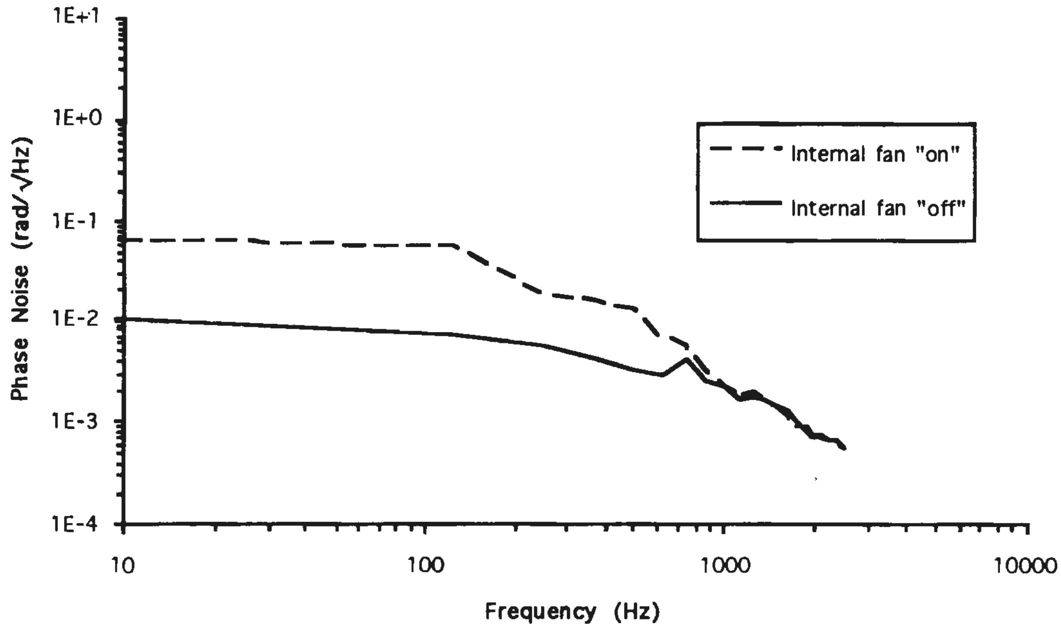

Figure 5. Comparison of Laser Phase Noise With an Optical Path Difference of 80 m for an HP External Cavity Laser With Fan "On" and Fan "Off"

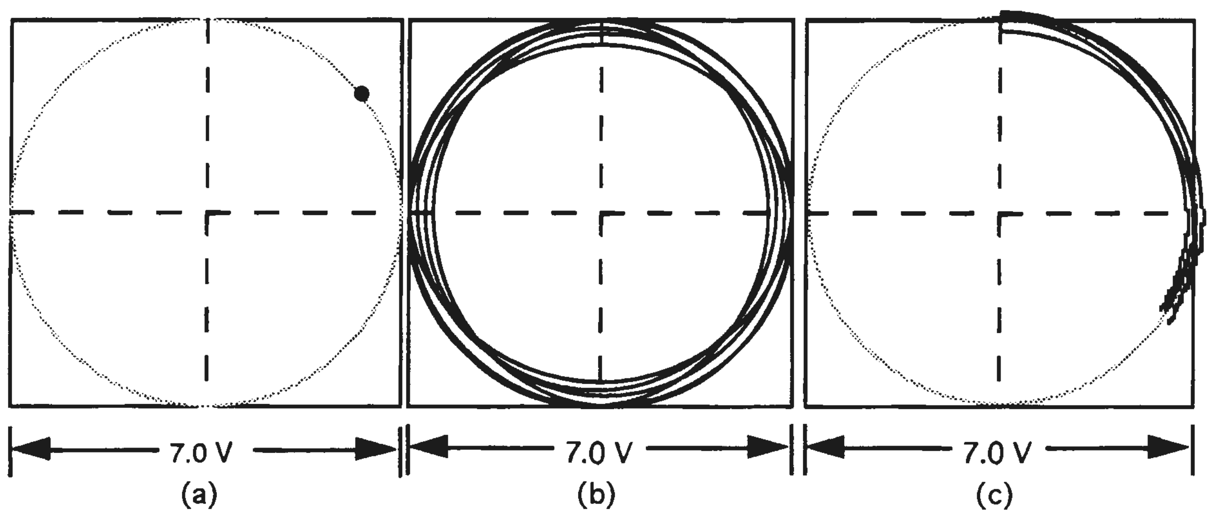

Figure 6. Sketch of Lissajous Patterns. (a) Ideal Pattern (b) During Phase Noise Measurement With Fan "On" (c) During Phase Noise Measurement With Fan "Off"

In interferometric sensor systems, near path balanced interferometers are typically used to reduce the effects of laser phase noise. Low phase noise characteristics of the laser alleviate path matching tolerances while providing low radian level phase detection sensitivities. For practical implementation in interferometric systems using time division multiplexing (TDM), sensors are typically matched to 2 cm. Additional mismatch can occur because the interferometer reference path can be shipboard while the sensing path is exposed to hydrostatic pressure. For an example of 2500 psi hydrostatic pressure, the additional mismatch would be approximately 20 nm, which is insignificant.

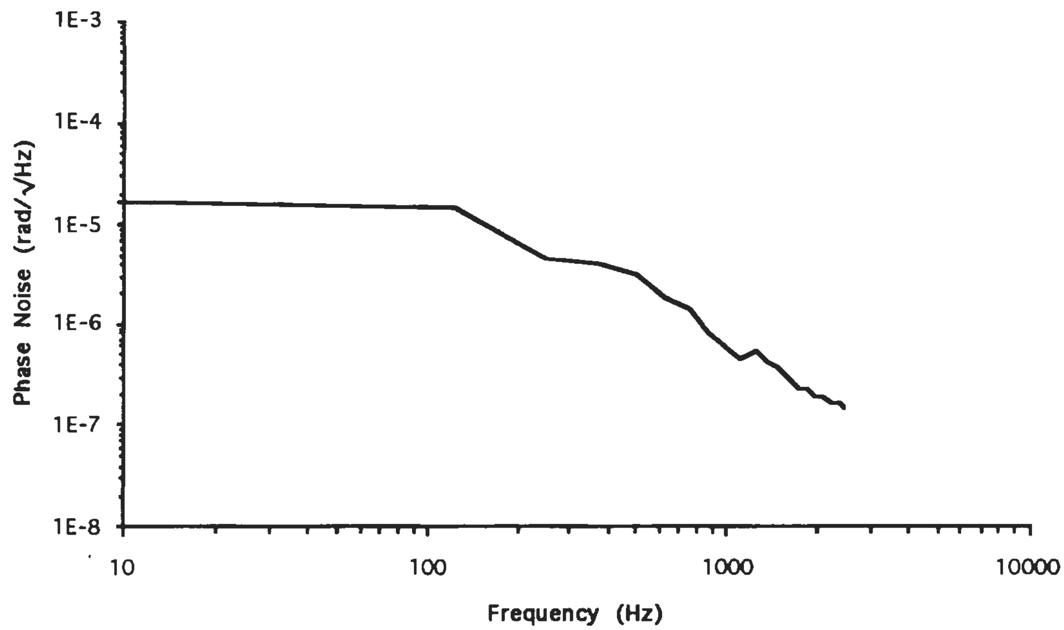

Figure 7. Laser Phase Noise Scaled for an Optical Path Difference of 2 cm for an HP External Cavity Laser With Fan "On"

In figure 7 the results from figure 3 are scaled for an optical path difference of 2 cm. The phase noise at a frequency of 1 kHz is $0.56\,\mu rad/\sqrt{Hz}$, corresponding to a laser frequency jitter of $0.22\ Hz/\sqrt{Hz}$. This noise level in itself is excellent for use in interferometric systems, however, larger path imbalances can produce noise terms that significantly add to system noise.

SUMMARY

The phase noise characteristics of an external cavity semiconductor laser have been measured using an unbalanced Mach-Zehnder fiber interferometer. This result is more than an order of magnitude lower than typically observed with semiconductor diode lasers, but nearly two orders of magnitude greater than that observed for a diode laser-pumped solid-state Nd:YAG laser. The vibration sensitivity of the laser was qualitatively assessed.

The external cavity laser is a good candidate for use in the development of interferometric fiber sensors with small path length differences (of the order of centimeters). It is recommended that further testing of this laser (and of other lasers for similar applications) include phase noise measurements while subjecting it to known vibration and acoustic levels.

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